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WHY DO SPACECRAFT CHARGE IN SUNLIGHT? DIFFERENTIAL CHARGING AND SURFACE CONDITION

Shu T. Lai

Space Vehicles Directorate
Air Force Research Laboratory
Hanscom AFB., MA 01731-3010

and

Maurice Tautz

AER / Radex, Inc.
131 Hartwell Avenue
Lexington, MA 02421

Abstract

Why do spacecraft charge in sunlight? The first reason concerns differential charging between the sunlit and dark sides. A monopole-dipole model describing the differential charging potential distribution yields interesting theoretical results. We compare the results with observations. The second reason concerns reflectance. Much attention has been paid in recent years to the effect of surface conditions on secondary emission, which plays an essential role in spacecraft charging. In comparison, little or no attention has been paid to the effect of surface condition on photoemission, which plays a dominating role in spacecraft sunlight charging. We present theoretical reasoning why highly reflective mirrors generate substantially reduced photoemission. We have calculated, by using the Langmuir orbit-limited current balance equation in 1-D, 2-D, and 3-D, the different surface potentials of various surface materials under typical space plasma conditions, satellite surface reflectivity values, and sunlight incidence angles. We present numerical results confirming that with substantially reduced photoemission, highly reflective surfaces would often charge to high negative potentials in sunlight.

Introduction

Spacecraft charging in space plasmas is due to the imbalance of ambient currents. At the geosynchronous environment, charging is often to high negative voltage because the ambient high–energy (keV) electron flux exceeds that of the positive ions by two orders of magnitude [*Reagan, et al.*, 1983; *Lai and Della-Rose*, 2001]. In response, the spacecraft charges to a negative potential repelling some of the incoming electrons. At equilibrium, all of the currents balance [*Whipple*, 1981; *Hastings and Garrett*, 1996].

Spacecraft charging to high negative voltage in sunlight has been a long-standing puzzle. Laboratory measurements show that the photoelectron flux emitted from typical surface materials illuminated by artificial sunlight greatly exceeds that of the ambient electrons under normal conditions at geosynchronous altitudes [*Feuerbacher and Fitton*, 1972; *Grard*, 1973; *Hitteregger, et al.*, 1959; *Stannard, et al.*, 1981]. If the outgoing electron flux greatly exceeds that of the incoming one, charging should be to positive voltage. Indeed, surface charging to a few positive volts is often observed in sunlight [*Lai, et al.*, 1986]. Surprisingly, high-level negative voltage (-kV) charging of spacecraft surfaces is sometimes observed [*Mullen, et al.*, 1986; *Lai*, 2004]. How can high-level negative potential charging occur on spacecraft surfaces? The answer is in differential charging and surface reflectance.

Potential wells and barriers can form as a result of differential charging between surfaces [*Fahleson*, 1978; *Mandell, et al.*, 1978; *Olsen*, 1980; *Olsen, et al.*, 1981; *Olsen and Whipple*, 1988; *Zhao, et al.*, 1996; *Nakagawa, et al.*, 2000; *Thiebault, et al.*, 2005]. Since photoelectrons are of low energy (1.2 eV in temperature), they are easily blocked by potential barriers and trapped in potential wells. The simplest, and most common, type of differential charging is in the monopole-dipole form [*Soop*, 1978; *Higgins*, 1979; *Besse and Rubin*, 1981; *Lai*, 2004]. With a fast spinning satellite, a monopole-quadrupole form is possible [*Tautz and Lai*, 2005].

Surface reflectance can reduce the photoelectron current emitted. We conjecture that high-reflectance surfaces emit little or no photoelectron current and therefore should charge to high negative potentials in hot plasmas despite sunlight [*Lai*, 2005].

Monopole –Dipole Model

The monopole-dipole potential distribution [*Schwartz*, 1972; *Besse and Rubin*, 1980] of a sphere is given by:

$$\phi(\theta, R) = K\left(\frac{1}{R} - \frac{A\cos\theta}{R^2}\right) \tag{1}$$

where ϕ is the potential at a point outside the sphere with a distance R from the sphere center. K is the monopole strength, A (<1) is the dipole strength normalized by K. When high-level charging occurs, K equals several kilovolts typically. The potential maximum, located at R_S, is given by

$$\left[\frac{d\phi(0^o,R)}{dR}\right]_{R=R_S}=0 \tag{2}$$

which gives $R_S = 2A$ from eq(1). The barrier, or the potential maximum, is located outside the spacecraft (R>1). Therefore, eqs(1,2) yield the inequality $1 > A > ½$. The barrier height B is given by

$$\frac{B}{K}=\frac{\phi(0^o,R_S)-\phi(0^o,1)}{K}=\frac{(2A-1)^2}{4A} \tag{3}$$

A barrier height B of even a few volts (-V) is sufficient to block photoemission, because photoelectrons emitted from geosynchronous satellites have low energies (1.2 eV in temperature [*Lai, et al.*, 1986]). For high-level charging, the ratio B/K is therefore nearly zero, which implies $A \approx ½$ in eq(3). As a result, eq(1) yields the ratio of the sunlit surface potential to that of the shaded surface:

$$\frac{\phi(0^o,1)}{\phi(180^o,1)}\approx\frac{1}{3} \tag{4}$$

In recent years, it has been found that the ambient electron temperature T_e is the most important parameter controlling the onset of spacecraft charging. All other space environment parameters are less important. Characterizing the ambient space plasma by T_e, we have found that, statistically, the ratio of the satellite potentials with and without sunlight is about 1/3 on the LANL geosynchronous satellites, no matter which satellite, year, or month [*Lai*, 2004; *Tautz and Lai*, 2005; *Lai and Tautz*, 2005]

Finally, we remark that the satellite potential distribution can be symmetrical about the spin axis if the satellite is rotating faster than the surface capacitance charging time. For arbitrary sunlight direction, the potential distribution, including any potential barriers, would be symmetrical not about the sunlight direction but, instead, about the spin axis. In such a case, monopole-quadrupole potential distributions occur [*Tautz and Lai*, 2005]. For the special case of sunlight perpendicular to the satellite spin, we have found the ratio (eq.4) becomes 2/5 [*Tautz and Lai*, 2005].

Surface Reflectance

In the spacecraft charging literature, it is a common practice to associate a photoemissivity value to a surface material without regard to the surface condition, surface reflectance, or the sunlight incidence angle. We stress that this deficiency needs to be improved. The photoelectron current $I_{ph}(R)$ emitted from a surface is given by [*Samson*, 1967; *Spicer*, 1972].

$$I_{ph}(R)=\gamma(\omega)I(\omega)[1-R(\omega,\theta)] \tag{5}$$

where I is the incident light intensity, γ the photoemissivity for normal incidence, θ the incidence angle, R the reflectance, and ω the frequency of the incident photon. Reflectance is a surface property depending not only on the frequency but also on the material, the smoothness, and the incidence angle [*Powell*, 1970]. For example, the reflectance at normal incidence of smooth pure aluminum [CDC Handbook, 2002] is about 0.9 at the Lyman Alpha frequency of sunlight (Figure 1).

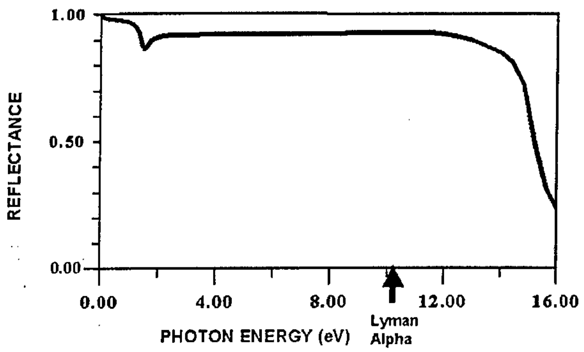

Figure 1 Reflectance of aluminum at normal incidence. (*Lai*, 2005)

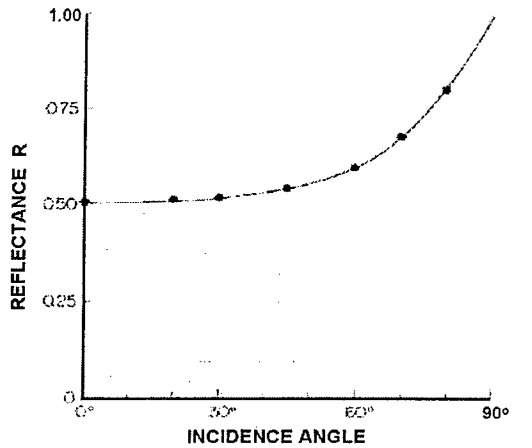

Figure 2 Reflectance of beryllium at various incidence angles. (*Lai, et al.*, 1986)

At grazing incidence, the reflectance is unity (Figure 2). Modern reflectors in space are highly efficient. With high reflectance, the reflected photons have nearly the same energies as the incident photons and therefore the photoelectron current generated is low. Physically, an incident photon needs to impart energy (for overcoming the work function and other attenuation factors) to the surface material in order to generate photoelectrons. The solar Lyman Alpha line is about 10 eV in energy, whereas a typical spacecraft surface material has a work function of about 4 to 5 eV. If the energy imparted is not enough to overcome the work function, no photoelectron is emitted. This part of the physics in this paper is well confirmed in laboratory experiments. What has not been confirmed is the following conjecture [*Lai*, 2005]:

Conjecture: Highly reflective surfaces charge to high negative potentials in hot plasmas not only in eclipse but also in sunlight.

We believe that it is worthwhile to conduct experiments in the future for confirming or rejecting the conjecture. If the conjecture is confirmed, there are important consequences. For example, mirrors and ordinary surfaces in space will charge to different voltages in sunlight, resulting in differential charging. Differential charging to high voltages is a space hazard, because it may lead to discharges between surfaces and/or instruments [*Lai*, 2001]. As another example, high negative voltage charging attracts positive ions, thus generating sputtering (multiple -kV). Sputtering is a very slow process but the cross-section peaks at typically multiple keV range. A smooth mirror being sputtered in space, day in and day out, regardless of sunlight or eclipse, will degrade faster than expected [*Lai*, 2005].

As a side remark, the photoelectrons emitted from surfaces with deep cleavages may be re-absorbed by the cleavage walls.

Onset of Spacecraft Charging in Sunlight

In the Maxwellian space plasma model, the onset of spacecraft charging in eclipse occurs at a critical temperature T* [*Lai, et al.*, 1982; *Laframboise, et al.*, 1982; 1983; *Lai, et al.*, 1983; *Lai*, 1991]. If the plasma electron temperature T is below T*, no charging occurs. Above T*, the charging voltage increases as the temperature T increases. This property has been observed on the Los Alamos National Laboratory geosynchronous satellites [*Lai and Della-Rose*, 2001]. In sunlight, the abundant and outgoing photoelectrons greatly affect the current balance. Naturally, a question arises: does a critical temperature T* exist in sunlight?

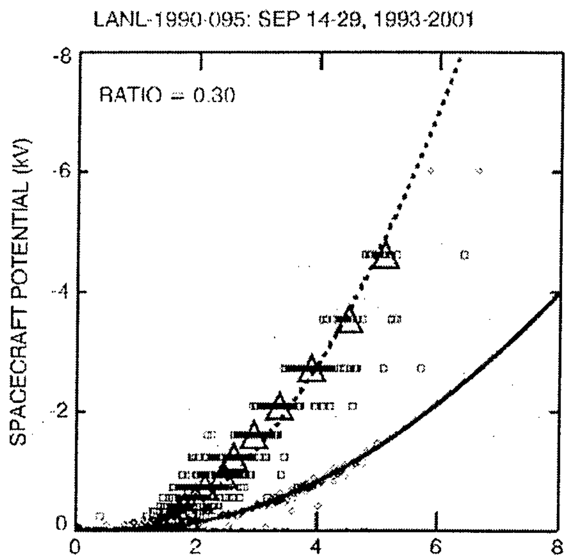

Figure 3 Charging in eclipse (upper branch) and in sunlight (lower). The data are quantized because of flux channels. The centroid of the temperature at every quantized level is shown as triangle. The ratio of the two branches is about 0.3. (*Tautz and Lai*, 2005)

From the result eq(4), we have the following conclusion: Since 1/3 of zero is zero while 1/3 of a finite number is finite, the critical temperature T* for the onset of spacecraft charging in the monopole-dipole model is the same as that in eclipse [Figure 3]. Likewise, T* is unchanged in the monopole-quadrupole model.

For high reflectance surfaces, the conclusion is different. Measurements in the laboratory and in space indicate that the ratio A of photoelectron flux to the ambient electron flux at geosynchronous altitudes is typically 20.

$$A = I_{ph} / I_e(\phi = 0) = 20 \qquad (6)$$

Since only one side of a satellite is in sunlight, A is halved and becomes 10. If a satellite features shadows in series, A can be reduced much further.

Suppose the angle dependent R is of the form $R(\theta) = 1 + (R_o - 1)\cos\theta$. The reflectance at grazing is unity. The photoelectron current I_{ph} (eq.5) is multiplied by $(1-R(\theta))$. With smooth pure aluminium surface material, R_o is about 0.9 [CDC Handbook, 2002], and at $\theta=60^\circ$, reduces the ratio A to:

$$A = I_{ph} / I_e(\phi = 0) = 0.5 \tag{7}$$

Besides, when a surface is inclined at an angle to sunlight, the effective surface area is reduced by another multiplicative factor of cos. With this example, we see that the (outgoing) photoelectron current can be less than the (incoming) ambient electron flux. Therefore, onset of spacecraft charging can occur in sunlight.

Using the usual Langmuir orbit-limited model [*Mott-Smith and Langmuir*, 1926], which is often a fairly good approximation for describing current balance at geosynchronous altitudes, we have calculated some cases of onset of charging in sunlight.

$$I_e(0)\left[1 - <\alpha + \eta>\right]\exp\left(-\frac{q_e\phi}{kT_e}\right) - I_i(0)\left(1 - \frac{q_i}{kT_i}\right)^{\alpha} = I_{ph} \tag{8}$$

where the notations are standard [see, for example, *Lai and Della-Rose*, 2001]. The power α in the Langmuir equation, eq(8), is 0, ½, or 1, for the geometries [*Mott-Smith and Langmuir*, 1926; *Laframboise and Parker*, 1973; *Lai*, 1994] of plane, cylinder, or sphere respectively. The results are presented in Figures 4, showing the onset of spacecraft charging even with the presence of photoemission. In these cases, the critical temperature T* at which onset of charging occurs in sunlight is different from that in eclipse. The value of T* in sunlight depends on the ratio A of photoelectron current to the ambient electron current.

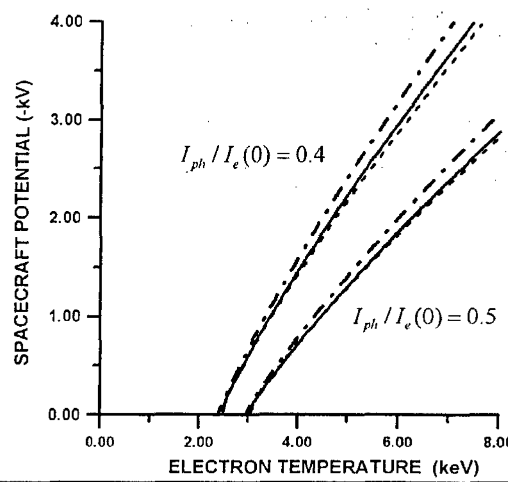

Figure 4 Calculated surface potential of aluminum oxide for two ratios of photoelectron to ambient electron currents. Dash-dot-dash is for 1-D, solid for 2-D, and dash-dash for 3-D. (*Lai*, 2005)

Conclusion

Since photoemission current exceeds the ambient electron current at geosynchronous altitudes, why do spacecraft charge in sunlight? We have considered two mechanisms: (1) differential charging, and (2) surface reflectance. If differential charging occurs between the sunlit side and the shadowed side occurs, one can model the system as a monopole-dipole. The monopole-dipole model results show that (a) the ratio of the potential on the sunlit side to that on the shadowed side is 1/3, and (b) the critical temperature T* is the same as that in eclipse. One can also model the system as a monopole-quadrupole model if the satellite spin is fast and perpendicular to the sunlight direction. The monopole-quadrupole model results show that the ratio becomes 2/5 and, by the same argument, the critical temperature T* is unchanged. In the second mechanism, we stress the importance of reflectance *R*. Surfaces with higher reflectance generate fewer photoelectrons. We conjecture that high reflectance surfaces charge to high negative potentials in hot plasmas, regardless of eclipse or sunlight. If this conjecture is confirmed, there are important consequences. Finally, we show some results of Langmuir orbit-limited model calculations of current balance without invoking differential charging. The results show that the value of the critical temperature T* is shifted depending on the ratio of the outgoing photoelectron current to the incoming ambient electron current. The photoelectron current depends, of course, on the surface reflectance.

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